BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 03098

SUBJECT: Impact of J Mission Payload Requirements on L/V Structures and Control Dynamics - Case 320

DATE: March 31, 1970

FROM: R. E. Hunter

ABSTRACT

Recent options have been presented by MSFC to increase the Saturn V payload capability to 107,000 lbs for Apollo lunar exploration missions (J missions). These options have assumed a baseline vehicle structures and control capability of 108,000 lbs. The impact of a 108,000 lb payload on the structure and control system capability of the Saturn V launch vehicle is herein assessed.

It is shown that no changes to Saturn V structure or control systems should be expected for J mission payloads provided the end S-IC boost accelerations are kept at or below 4.0g.

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MEMORANDUM FOR FILE

INTRODUCTION

At Apollo Lunar Exploration Mission meetings, MSFC has presented options to increase the Saturn V maximum injected payload capability from the present 101,500 lbs to 107,000 lbs for AS-511 and subsequent vehicles.(1) These options have been presented assuming a baseline vehicle structures and control payload capability of 108,000 lbs. The impact of a 108,000 lb payload on the structural adequacy and control system capability of the Saturn V launch vehicle is herein discussed.

LAUNCH VEHICLE CHANGES FOR BASELINE J MISSION

Table 1 lists the changes proposed for the Saturn V launch vehicle in order to achieve a baseline payload commitment of 105,500 lbs. Additional options being considered for increasing payload capability to the desired 107,000 lbs are listed in Table 2.(1) Only the two underlined changes will have any impact on the structural capability of the launch vehicle.

Increased time delay from 1.2 sec. to 1.6 sec. on S-IC CECO will increase peak axial acceleration. The majority of the launch vehicle structure is designed for this load condition, and the impact of increased S-IC end boost accelerations are discussed at length herein.

S-II stage additional mainstage propellant will affect structural loads during the most critical loading periods. Current estimates from MSFC are that an additional 1,500 lbs of propellant will be added to the S-II stage; this amounts to a 0.14% increase in total S-II weight. The S-II aft LOX bulkhead is critical during peak accelerations at S-IC end boost. Current mission safety factors for the aft LOX bulkhead are about 1.4 for the S-IC end boost condition.(2) It would take a 10% increase in S-II LOX load in order to lower this safety factor below the required 1.3 for the lightweight S-II. Increased S-II LH_2 loading is of no concern to S-II tankage because the LH_2 forward bulkhead and tank wall are critical at S-II end boost, and S-II end boost loading conditions will remain unchanged. The S-II common bulkhead is critical during pre-launch operations, and will be unaffected by the additional propellant.

The S-II aft skirt and the S-IC skirts and tank walls will be affected by increased S-II LOX loading. The net affect will be an increase in load, at a given vehicle station, for the critical time of S-IC end boost, in proportion to the percentage increase in total weight above that station.

L/V STRUCTURES

Small increases in payload have a small or negligible affect on the ability of the Saturn V launch vehicle to survive the critical loading periods of pre-launch, max $q\alpha$, S-IC CECO, S-IC OBECO, and S-IC/S-II separation. With the exception of individual stage thrust structures and portions of the S-II tankage, these conditions establish all launch vehicle design loads for nominal flight.[2,3]

Pre-launch loads, from maximum ground winds on a vehicle without propellants, determine the lowest safety factor that the launch vehicle is exposed to. With the vehicle empty, on the pad, without the mobile service structure present, and without the damper attached, a wind speed of 40 knots will create a minimum safety factor of 1.26 in the S-II LH_2 tank at station 1902.[2] This load is primarily from bending due to vortex shedding; a 7,000 lb payload increase would not significantly alter this condition. This load occurs prior to astronaut boarding, and a minimum safety factor of 1.25 has been accepted.

Max $q\alpha$ loads are now calculated using KSC directional winds and wind biased trajectories.[2] The maximum operational wind loads, which occur for a March launch, are approximately 68% of design loads, based on a 75 m/sec. omnidirectional wind. J mission payload weights affect launch vehicle max $q\alpha$ loads most at the forward end of the launch vehicle. The minimum safety factor in the S-IVB-IU area, under maximum operational wind conditions, is approximately 1.8 at station 3222.[2,3] Preliminary calculations by North American Rockwell of J mission $q\alpha$ loads indicate no perceptable change in loads at the SLA/IU interface (station 3258), over current Apollo mission loads.

Using AS-504 load predictions at max $q\alpha$ as representative loading for a launch in the month of March,[2] and using current assessments of launch vehicle capability,[3] the minimum launch vehicle safety factor is 1.34 at the S-II forward skirt (station 2519). The minimum safety factor for J missions will not be significantly different from the above, and small changes are acceptable since the required safety factor is 1.30 for the light-weight S-II.

S-IC/S-II separation creates design tensile loads in much of the S-IVB and spacecraft. In all cases the safety factors are so far in excess of the 1.4 and 1.5 required, that the proposed payload changes could not increase separation loads sufficiently to reduce safety factors below specifications.[4]

Current plans for the J missions limit the S-IC end boost acceleration to a maximum of 4.0g. End boost structural safety factors at a particular vehicle station are determined from local temperature, internal pressure, peak axial accelerations, and total weight above that station. By comparing end boost conditions and corresponding safety factors for Apollo 11 and a typical J mission, the impact of the proposed increased payload can be evaluated.

Apollo 11 maximum loads and safety factors for a nominal 3.73g S-IC CECO acceleration, as determined from the Apollo 11 operational trajectory, are shown in Table 3.[5] Shown in Table 4 for comparison purposes are Apollo 11 loads assuming a 4.0g S-IC end boost acceleration. The increase in temperature for the 4.0g case is due to the corresponding delayed center engine cutoff. In Table 5 the affect of an added 7,056 lb payload* to that flown on Apollo 11 is shown. Note that the payload increase noticeably reduces safety factors only at the IU and S-IVB forward skirt, where 7,056 lbs is a significant percentage of the total weight above

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*Apollo 11 payload + 7,056 lb = 108,000 lb.

that point. Fortunately, the safety factors in this region are large enough that the increased payload is of little concern. Below the S-IVB propellant tanks the added payload weight is a small percentage of the total weight above any one station, and the changes in safety factors due to added payload are negligible, when compared to the effects of an increased S-IC end boost acceleration.

In Table 5 the lowest end boost launch vehicle safety factor for a 108,000 lb payload is 1.335 in the S-II aft skirt. Current MSFC Specifications require a 1.4 safety factor for the launch vehicle, with a waiver to 1.3 for the "light weight" S-II stages (S-II-4 through S-II-10). The S-IC forward skirt safety factor of 1.373 (Table 3) does not meet the 1.4 requirement, but is significantly greater than the lowest S-II safety factor.

If performance capabilities require greater than a 4.0g end boost acceleration, in order to inject a 108,000 lb payload, launch vehicle safety factors can become a concern. A 4.35g S-IC end boost acceleration for a J mission would produce a minimum launch vehicle safety factor of 1.23 in the S-II aft skirt and a corresponding safety factor of 1.26 in the S-IC forward skirt.[5] Current plans do not require greater than a 4.0g S-IC end boost acceleration to meet J mission launch vehicle performance requirements.

LAUNCH VEHICLE CONTROL DYNAMICS

Control system stability analysis of the Saturn V launch vehicle, for present missions, has shown lower stability margins during S-IC and S-II flight than during S-IVB flight.[6] Representative changes in present inertia properties for a typical J mission are shown in Table 6. These changes are well within present 3σ tolerances for S-IC and S-II burn, and will not significantly affect present results. Changes in elastic body dynamic properties during S-IC and S-II burn can be expected to be small compared to 3σ tolerances on present calculations.

Control system gain and slosh peak gain margins during AS-507 S-IC burn are below their present stability criteria. "The criteria violations are acceptable because they are primarily due to slosh, the oscillations do not couple into vehicle dynamics, and the slosh damping increases as slosh wave height increases."[6] Additional payload will not affect slosh dynamics and thus will not affect this critical area.

During AS-507 S-II burn the only marginal stability condition occurs in the second bending mode peak gain margin just prior to LET jettison, where nominal gain stability is 2.3 db and 3σ gain stability is -0.6db (unstable). The 3σ phase margin available at this time is 169.9° compared to a 3σ stability criteria of 75°, thus assuring second bending mode stability during S-II burn.[6] After LET jettison, the minimum second mode 3σ gain stability is 15 db at S-II end boost. A 108,000 lb payload would have to cause major changes in second mode phase relationships in order to significantly affect this result. There is no reason to expect any such change to occur.

A summary of stability margins during the S-IVB burn for the AS-507 vehicle is shown in Table 7.[6,7] Shown are both nominal and 3σ stability margins as well as the required margin. In all cases, the 3σ margin is considerably above the required margins. Shown in Table 8 are the affects of 3σ uncertainties in structural stability. Note from Tables 6 and 8 that the increased inertia and center of gravity shift due to increased payload, will increase the stability margin during S-IVB burn. Payload increases for a J mission will lower modal frequencies but the change can reasonably be expected to be 3% or less for all modes during S-IVB burn.[8,9] Small changes in bending mode slopes will also occur but the stability analysis indicates that large changes in slope can be tolerated, based on present 3σ margins.

Spectral analysis of flight instrumentation on previous flights indicates the presence of lateral oscillations in the first four bending modes during S-IC burn. The frequencies of these oscillations agree well with, but are generally higher than the analytical values used in control system stability analysis.[10,11,12] Vehicle to vehicle modal frequency variation, as measured by flight instrumentation, has been small.[10,11,12]

SUMMARY

The total change in mass properties and structural dynamics during S-IC and S-II boost are negligible when compared to 3σ parameter variations used to verify stability. When appropriate parameters are defined for the J missions, new stability margins will be calculated but there is no reason to expect that any changes to existing control system hardware will be necessary.

No changes to the Saturn V launch vehicle structure will be necessary to support a 108,000 lb injected payload, provided the S-IC end boost acceleration is limited to 4.0g.

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2031-REH-jct

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Attachments

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10. "Saturn V Launch Vehicle Flight Evaluation Report AS-503 Apollo 8 Mission," MSFC, February 20, 1969.

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12. "Saturn V Launch Vehicle Flight Evaluation Report AS-506 Apollo 11 Mission," MSFC, September 20, 1969.

TABLE 1

L/V Changes Required for Baseline Payload Commitment for J Missions (105,500 lb)

1. Optimize propellant loading for first opportunity for TLI.
2. Reduce FGR to 10 m/sec.
3. Reduce FPR to 2 sigma.
4. Increase time delay from 1.5 sec to 1.85 sec on S-II stage.
5. Remove S-II LOX step pressurization.
6. Increase time delay from 1.2 sec to 1.6 sec on S-IC CECO.
7. Open loop PU system in S-II and S-IVB stages.
8. Deletion of ullage and retro rockets.
9. S-II LH_2 timer.
10. S-II stage additional mainstage propellant.
11. S-II mixture ratio change (AS-511 and 512).
12. Additional IU battery for lunar impact.

TABLE 2

Additional Payload Increase Options to Meet Desired 107,000 lb Payload Capability

		Payload Increase
1.	Constrain launch azimuth between 87° and 96°.	700 lb
2.	Remove IU battery required for lunar impact tracking.	200 lb
3.	Lower earth parking orbit to 90 n.m.	600 lb

TABLE 3

Apollo 11 at 3.73g CECO

100,944 lb Injected Payload

DESCRIPTION	STATION (in)	TOTAL LOAD (lb/in)	TEMP (°F)	ULTIMATE CAPABILITY (lb/in)	SAFETY FACTOR*,[5]
IU	3222	548	100°	1120	2.04
SIVB Aft Skirt	2832 Aft (A)	1745	225°	3043	1.74
	2746 Forward (F)	1769	225°	3043	1.72
SII Forward Skirt	2519 A	1198	225°	1832	1.53
	2387 F	1218	275°	1832	1.50
SII Aft Skirt	1848 A	4387	210°	6364	1.45
	1760 F	4397	210°	6575	1.48
SIC Forward Skift	1541 A	4414	205°	6583	1.49
	1401 F	4425	205°	6583	1.49

$$\text{*Safety Factor} = \frac{\text{Ultimate Capability Based on Test, Analysis, \& Flight Experience}}{\text{Total Load}}$$

TABLE 4

Apollo 11 at Assumed 4.0g CECO

100,944 lb Injected Payload

DESCRIPTION	STATION (in)	TOTAL LOAD (lb/in)	TEMP (°F)	ULTIMATE CAPABILITY (lb/in)	SAFETY FACTOR
IU	3222	588	105°	1080	1.837
S-IVB Aft Skirt	2832 Aft (A)	1877	230°	3014	1.60
	2746 Forward (F)	1900	230°	3014	1.58
S-II Forward Skirt	2519 A	1289	279°	1818	1.41
	2387 F	1310	279°	1818	1.39
S-II Aft Skirt	1848 A	4710	213°	6314	1.34
	1760	3720	213°	6480	1.37
S-IC Forward Skirt	1541 A	4748	212°	6555	1.38
	1401 F	1760	212°	6555	1.38

TABLE 5

J Mission at Assumed 4.0g CECO

108,000 lb Injected Payload*

DESCRIPTION	STATION (in)	TOTAL LOAD (lb/in)	TEMP (°F)	ULTIMATE CAPABILITY (lb/in)	SAFETY FACTOR
IU	3222	5055	105°	1080	1.784
S-IVB Aft Skirt	2832 Aft (A)	1855	230°	3014	1.59
	2746 Forward (F)	1918	230°	3014	1.57
S-II Forward Skirt	2519 A	1302	279°	1818	1.396
	2387 F	1323	279°	1818	1.374
S-II Aft Skirt	1848 A	4723	213°	6319	1.335
	1760 F	4733	213°	6480	1.365
S-IC Forward Skirt	1541 A	4761	212°	6555	1.377
	1401 F	4773	212°	6555	1.373

*L/V weights assumed same as Apollo 11

TABLE 6

Effect of J Mission Payload on Apollo 11 Mass Properties

Apollo 11 Injected Payload 100,944
J Mission Injected Payload 108,000
(ΔW = 7,056 lb)

	WEIGHT CHANGE	MOMENT OF INERTIA CHANGE	C.G. CHANGE
LIFT OFF	+.103%	+1.08%	+.195% (2.34")
END S-IC	+.386%	+1.14%	+.332% (+5.97")
START S-II BURN	+.485%	+2.15%	+1.03% (+5.75")
END S-II BURN	+1.50%	+1.58%	+.76% (+8.68")
START S-IVB BURN	+1.92%	+1.88%	+1.65% (6.68')
END S-IVB SECOND BURN	+5.064%	+.06%	(0%) 0(0)

TABLE 7

AS-507 Minimum Stability Margins During S-IVB Burn [6,7]

	NOMINAL STABILITY MARGIN	3σ STABILITY MARGIN	3σ MARGIN REQUIREMENT
CONTROL SYSTEM PHASE MARGIN (deg)	33.5	27.6	15
CONTROL SYSTEM GAIN MARGIN (db)	9.2	7.3	3
1st BENDING GAIN MARGIN (db)	17.2	10.6	3
2nd BENDING GAIN MARGIN (db)	28.5	21.4	3
3rd BENDING GAIN MARGIN (db)	18.7	9.6	3
4th BENDING GAIN MARGIN (db)	22.3	12.5	3
LOX SLOSH PHASE MARGIN (deg)	38.5	27.7	20

TABLE 8

AS-507 S-IVB Stability Analysis

Effect of 3σ Variation in Structural Dynamic Parameters[6,7]

PARAMETER	MODE 1*	MODE 2*	MODE 3*	MODE 4*
MODAL FREQUENCY	-3/.7	-10/3	-20/4	-20/5.6
BENDING MODE SLOPE AT RATE-GYRO	+34.4/2.4	+34.4/2.4	+80/5.1	+80/5.1
BENDING MODE SLOPE AT GIMBAL	+10/.4			
BENDING MODE SLOPE AT PLATFORM	+34.4/.3			
STRUCTURAL DAMPING	-50/6	-50/5.7	-50/6.0	-50/6.0

	VARIATION	CONTROL SYSTEM PHASE MARGIN LOSS	CONTROL SYSTEM GAIN MARGIN LOSS	LOX SLOSH PHASE MARGIN LOSS
CENTER OF GRAVITY	-3.5%	.1°	.9db	2.8°
PITCH-YAW MOMENT OF INERTIA	-3.0%		.5db	1.4°

*Variation %/Loss in stability margin db

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